

MODELLING THE EFFECT OF INTRODUCING MPAS IN A COMMERCIAL FISHERY: A ROCK LOBSTER EXAMPLE

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Abstract

The effect of introducing a large marine protected area (MPA) into a managed commercial fishery was investigated using a spatially explicit, size-structured model. The stock dynamics approximated the biology of Tasmanian rock lobsters in that adult movement was very limited while larval dispersal was widespread.

If an MPA displaces fishing effort into the area that remained open to fishing, then fishing mortality (F) would be expected to rise. The effect of this increase in F would depend on the level of stock depletion, with three possible main outcomes:

1. If the population was only lightly depleted and above the level of B_{MSY} then fishing the open areas harder increases the depletion level but renders the stock more productive. Depending on the exact level of depletion and the increase in F , a new equilibrium was reached.
2. Highly depleted population, below B_{MSY} ; fishing the stock harder depletes it further, making it even less productive, if fishing maintained, leads to a fishery collapse.
3. If stock already close to collapse, then displaced effort would be so ineffective that the MPA could act to increase recruitment levels and make the whole stock relatively more productive.

The model suggested that introducing large MPAs may be harmful without a reduction in catch at least equivalent to that displaced from the MPA. An MPA without concomitant catch reduction could lead to further stock depletion in open regions. This can lead to a new equilibrium or fishery collapse, depending on the level of stock depletion when the MPA was introduced. If the fishery was close to or already collapsed, an MPA was likely to be beneficial to stock recovery because of its contribution to recruitment.

Keywords: modelling, rock lobster, marine protected areas, commercial harvesting, benefits

INTRODUCTION

Marine Protected Areas (MPAs) have been advocated in many circles as an option for fisheries management because of a widely perceived concern over the failure of traditional fisheries-management methods. In addition it is argued that MPAs are needed to protect biodiversity. In Australia the National Representative System of Marine Protected Areas (NRSMPA) is at the centre of the Australian and New Zealand Environment and Conservation Council's (ANZECC 1998) plan to secure the long-term future of Australia's coastal ecosystems. The main focus of this plan is the conservation of biodiversity through a comprehensive, representative and adequate system of MPAs.

As harvest refugia, it is suggested that MPAs offer a range of potential benefits for the management of fisheries. Included are the protection of spawner stock, acting as a source of propagules

and/or surplus adults, acting as reference areas against which the effects of fishing may be quantified, and acting as an insurance against the failure of conventional management.

The benefits to fisheries are said to arise out of the return to a more natural population age structure (more large animals), which, by virtue of the relationship between fish size and egg production, increases the reproductive output of the population. An MPA thus acts as a source of eggs and larvae and a source of surplus larger fish that recruit to the fishery adjacent to the MPA.

The number of MPAs established around the world is on the increase, at present around 1300 in more than 100 countries (Roberts and Hawkins 2000). Despite this, only 0.5% of the world's oceans are in MPAs and our understanding of the potential outcomes of MPAs remains largely anecdotal. More research needs to be done before we can clearly describe their effects.

A survey of the literature on the effects of the establishment of MPAs provides clear evidence of the fact that resident fish and other species recover from the impact of exploitation and are both of a larger average size and more abundant in reserves (Ward *et al.* 2001). This is an expected result that has stood up to examination in tropical and temperate waters for a range of different fish and invertebrate species.

More importantly, from a fisheries perspective, it has been shown in some cases that yield in adjacent fisheries improves at a local scale. As an example this has been observed in New Zealand where lobster fishermen target good catches of fish close to the boundary of the Leigh Reserve. Studies in South Africa have shown how the catch per unit effort (CPUE) of reef fish in areas adjacent to the large deHoop Nature Reserve have increased. The study by Russ and Alcala (1994) showed how a small Philippine coral reef fishery was maintained in the presence of an MPA.

The evidence that MPAs function as a source of eggs and larvae is less convincing. There is some evidence that this is a likely outcome for inshore reef fish of a large marine reserve in South Africa, the Tsitsikamma National Park, but generally little else is known of this potential benefit (Tilney *et al.* 1996). A Tasmanian study has suggested that MPAs contribute to egg production in lobster, but the overall impact is small relative to the egg production coming from the whole population around Tasmania (Edgar and Barrett 1999).

In this study we examined the effect of introducing a large MPA into a managed commercial fishery using a spatially explicit, size-structured model. The stock dynamics approximated the biology of Tasmanian rock lobsters (*Jasus edwardsii*), in that adult movement was very limited whereas larval dispersal was widespread. The strategy used to explore the effects of MPAs involved

1. Initiating a stock of numerous populations in an equilibrium, unfished state.
2. Harvesting to deplete the model populations to a known level using selective fishing mortality.
3. Introducing the maximum sustainable harvest rate for the given level of depletion either with or without a large MPA.

The work is part of a larger study examining the effects of MPA as a fisheries management tool, funded by the Fisheries Research Development Corporation of Australia.

SOURCES OF MODEL UNCERTAINTY

Unfortunately, there are aspects to such MPA modelling that are difficult to describe owing to a lack of previous experience or understanding.

The first major source of uncertainty concerns how fishers would respond to having a significant geographical part of a fishery closed to fishing. This equates to uncertainty about fleet dynamics in the presence of large closed areas. Because no information is available and each situation is likely to be unique, the only strategy available for dealing with the problem is to attempt to model a number of alternative fleet responses. Alternatives included distributing effort into available fishing grounds in proportion to the catch already taken from those grounds, distributing effort proportionally into the top 50% of areas for catch from the fishery, and other strategies suggested by the circumstances found in particular fisheries. Distributing displaced effort into remaining areas in proportion to the amount of effort already expended in those areas is the least likely to cause problems for the fishery. Any other strategy that relies on focusing effort into particular areas is more likely to lead to a serial depletion of open areas. Here, only the most conservative scenario is considered: proportional dispersal of displaced effort

The second major source of model uncertainty relates to which stock–recruitment relationship to use. An aim of the larger project, of which this study is a part, is to examine the potential effect of introducing MPAs on the Tasmanian rock lobster and abalone fisheries. However, our understanding of the recruitment processes in these species is limited. We certainly do not know which areas are predominantly sources of larvae and which are predominantly sinks for larvae. It seems quite possible that no area is always one or the other. As with the fleet dynamics, the only option when such unknown processes must be included in a modelling framework is to try a number of options and determine the outcomes contingent on each possibility considered. Alternative stock–recruitment relationships were considered, as well as different arrangements of sources and sinks.

In the work considered here the focus is on rock lobsters. Recruitment is considered on a stock-wide basis, with settlement levels in different areas reflecting the previous yield taken from those areas through the history of the fishery (used as a proxy for productivity). We are not reporting any work on arrangements of sources and sinks of recruitment. It appears intuitively obvious that if the major source of recruitment for a fishery can be found and protected, then there should be benefits for the fishery; and this can

easily be confirmed by use of our general model. Some recently published modelling work supports the benefits that may accrue to a fishery if the recruitment sources are protected (Apostolaki *et al.* 2002).

The model developed during this project was deterministic. A stochastic version would be a simple change, but for the purposes of the project objectives the outputs are more clearly defined by keeping the model deterministic. In addition, the inclusion of random variation to the recruitment, settlement, and patterns of fleet dynamics (fishing mortality) would tend to reduce any positive effects that might be shown through the introduction of MPAs. Because the outputs of the modelling generally did not demonstrate positive effects for fisheries from MPAs, in order to make the final conclusions more defensible, efforts have been made to select assumptions that could be considered as biased towards a positive effect of MPAs.

MODEL STRUCTURE

Rock lobsters are rather difficult to age, so the model structure took the following structural form:

- It was size-structured by sex (to allow for the sexual dimorphism of rock lobsters). The size-structured nature of the model permits more realistic population dynamics (size at maturity, recruitment and growth by transition matrix), it permits fishing to be size selective, and it permits predictions about the impacts on the population structure (age-structure could easily be added if required). In the model there were 17 size classes of 10 mm from 25 mm up to 185 mm.
- There was an annual time step to the dynamics of growth, recruitment and mortality. Half of natural mortality was applied, then growth and recruitment occur, followed by any movement between areas. Fishing mortality is then applied and finally the remaining half of natural mortality.
- The model was spatially explicit; any number of populations could be defined, dependent only upon availability of information relating to catch and growth. The coastline may be linear or may connect end-to-end (i.e. an island); this detail has implications for movement and fleet dynamics. The separate areas might be statistical reporting areas or assessment areas or might be completely hypothetical, as with the work reported here.
- Recruitment is deterministic. In the work reported here a Beverton–Holt stock–recruitment relationship was used. Settlement

success in an area is dependent upon the total yield taken from each area (taken as a proxy for available productive habitat).

- A single-species approach was used. Species interactions, e.g. between rock lobsters and abalone, are ignored.
- Recruitment is spread across all areas and movement of adults in each time-step is restricted to adjacent areas.

MODELLING STRATEGY

The detailed model of the Tasmanian rock lobster fishery was extremely specific. The conclusions drawn about the potential impacts of introducing no-take MPAs were idiosyncratic to the fishery. Large areas of Tasmania could be closed to rock lobster fishing but because these contribute very little to the fishery they would have no noticeable effect. Other areas are so significant to the fishery that closing them, without reducing catch appropriately, led very quickly to a fishery collapse within the model. The effects of closing areas of intermediate importance depended closely upon the dynamic response of the fleet to the closures. If effort was distributed in proportion to stock availability this could lead to stability (assuming that the closures did not represent more than the present level of rebuilding in the stock). If effort was focussed into only a few areas, this led to their decline, which in turn led to decline in other areas; then the fishery could eventually collapse though a process of serial depletion. Redistributing effort in proportion to stock availability generally led to least fishery damage. However, in reality, it is likely that fishers would not be able to fish in this relatively risk averse manner.

To avoid such idiosyncratic answers to generic questions, the strategy was adopted of a defined set of populations with identical properties of growth, movement, catch history and reproduction, so that the issues of different productivity, different catch histories, unknown fleet dynamics and differential recruitment were removed from consideration. These hypothetical populations could number either 10 or 20 to permit the simple closure of 10% or 5% of the fishery. The conclusions drawn from this simplified, idealized stock are therefore general. Nevertheless, the population dynamics approximate those of rock lobsters living in and around Maria Island on the east coast of Tasmania. Care needs to be taken when considering species with radically different life cycles or biology.

The strategy adopted in the present study was to define ten hypothetical populations each with identical growth and productivity. A growth-

transition matrix determined from a rock lobster tagging study conducted in the Maria Island marine reserve on the east coast of Tasmania was used to describe the sexually dimorphic growth of the two sexes (Fig. 1). Males obviously grow much larger and heavier than females.

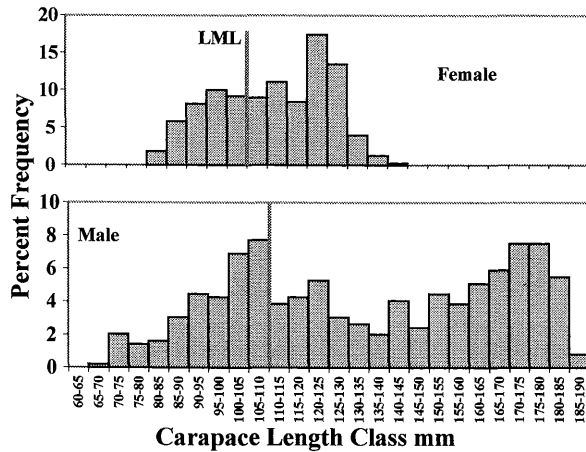


Fig. 1. Carapace lengths (5 mm classes) of rock lobster (*Jasus edwardsii*) captured and tagged in the Maria Island marine reserve after ten years of no commercial fishing. Smaller sizes are present only in low numbers because of the selectivity of the fishing gear. LML is the legal minimum length.

The dynamics of the hypothetical stock of ten populations could be followed through time with or without fishing, and with or without an MPA. By growing the population without fishing the equilibrium levels of recruitment could be defined. Fishing mortality could be imposed on the unfished population and the consequent depletion in biomass and numbers could be monitored. At any stage, the surplus production from the stock could be determined. This would be the catch level that, if applied, would leave the stock at the same productivity level each year (it would leave the population in equilibrium).

By application of a series of different excess levels of fishing pressure, the stock could be depleted to different levels, the surplus production at those depletion levels determined and, in that way, a curve of surplus production against depletion of legal-size biomass determined (Fig. 2). If an MPA was introduced by closing one of the ten hypothetical populations this would be equivalent to reducing the productivity by 10%. The absolute difference this would make to the productivity would be greater near the maximum sustainable yield than when the stock is only lightly depleted (Fig. 2). In addition, the size-distribution of the stock changes with increasing depletion of legal-size biomass in a manner that reflects what has been seen in the real fishery (Fig. 3).

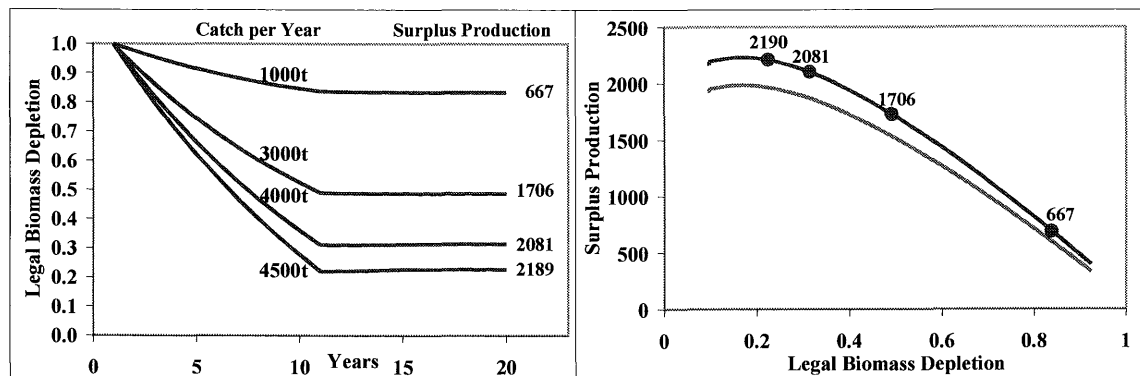


Fig. 2. Hypothetical populations of rock lobster fished at high levels for ten years (catch per year) demonstrate different degrees of stock depletion.

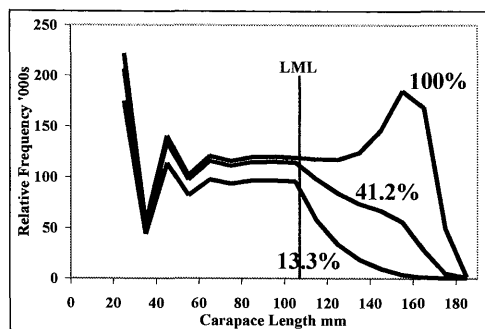


Fig. 3. Changes to the expected size-frequency distribution of male rock lobster at different levels (%) of remaining legal-size biomass (depletion).

Using this model, we investigated the effects on the stock dynamics (both inside and outside closed areas) of introducing a no-take marine reserve equivalent to 10% of the production when the stock was at different levels of depletion.

At each level of stock depletion, there is a catch level that can be maintained through time, defined as the surplus production (Fig. 2, left panel). With different levels of catch per year, the curve of surplus production against stock depletion level can be determined (Fig. 2, right panel). If one of the hypothetical populations is closed to fishing, then the available productivity is immediately reduced to only 90% of the original (lower line in the right panel). The classic surplus-production curve can be seen. The model dynamics become relatively unstable beyond the peak productivity (the Maximum Sustainable Yield). The depletion curve of numbers of animals is more symmetrically shaped around 50% because of the non-linear relationship between size and weight; the larger animals are the first to go, and they weigh the heaviest (Haddon *et al.* unpublished).

The fishing down of the large mode of accumulated older animals is apparent and reflects what has been seen in the fishery on the east coast of Tasmania. The peaks at smaller size classes relate to particular cohorts growing into the population on the yearly time step (Haddon *et al.* unpublished).

RESULTS

Introduction of an MPA when stock is only slightly depleted

When an MPA is introduced (Fig. 4), the available productivity drops from 1200 t to 1090 t. If the Total Allowable Catch (TAC) is not reduced accordingly, the stock needs to be depleted to

62.6% (rather than 67.1%) so that the populations remaining open to fishing can produce the extra catch required (Fig. 4).

A TAC of 1694 t would imply a yield of 169.4 t from each of the ten populations, which would occur sustainably when the stock was depleted to 49.6% of the unfished legal biomass (Fig. 4). If an MPA were introduced, then the nine populations remaining open to fishing would produce only 152.3 t sustainably. To produce the required TAC the stock would have to be depleted to 41.5% of unfished biomass so that the nine remaining populations could produce at a yield of 188.2 t each (Haddon *et al.* unpublished).

In the case of an undepleted stock, the introduction of an MPA leads to a higher fishing mortality outside the MPA and a greater depletion of the stock, but the fishery is still sustainable and the biomass within the MPA increases (Fig. 5).

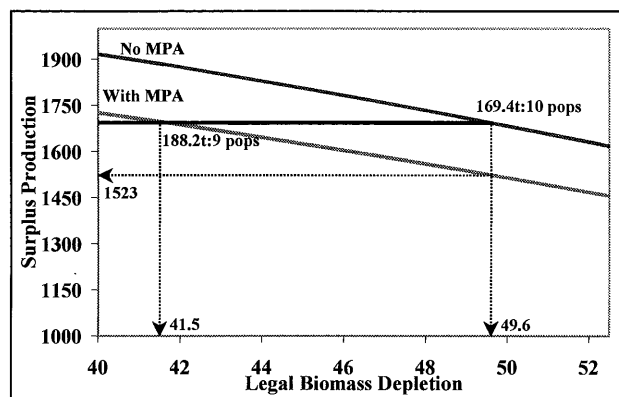


Fig. 4. Impact (modelled) of a marine protected area (MPA) on Total Allowable Catch of rock lobster.

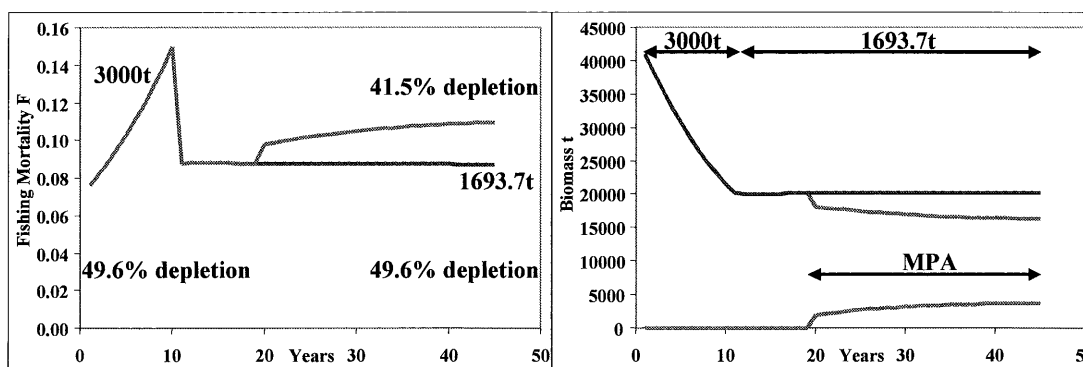


Fig. 5. Impact (modelled) of introducing a marine protected area (MPA) into a rock lobster fishery when it is not yet at maximum productivity, relative to the scenario of no change.

In this case, introduction of an MPA leads to a higher equilibrium level of fishing mortality outside the MPA (Fig. 5, left panel) and a decrease in the legal biomass outside the MPA (Fig. 5, right panel). At the same time, the biomass inside the MPA increases until both inside and outside areas attain a new equilibrium.

Introduction of an MPA when stock is close to maximum production

In the model, if the stock is at a legal biomass near to that which can generate the maximum productivity, then introduction of an MPA enclosing 10% of available production can lead to a fishery collapse, if the TAC is not reduced appropriately (Fig. 6). In the example, with a 30.1% depletion of legal-size biomass the fishery can take 2100 t each year in a sustainable manner. If the MPA is introduced, the nine remaining populations still open to fishing produce only approximately 1900 t sustainably even at the maximum productivity at a depletion level of 17.5%.

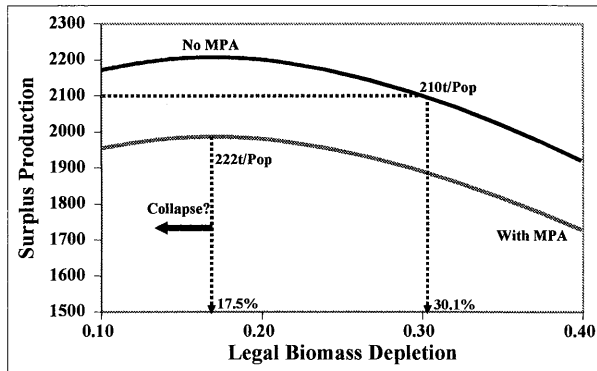


Fig. 6. Impact (modelled) of a marine protected area (MPA) when rock lobster stock is close to maximum production.

However, the strategy of depleting the legal-size biomass further to increase the productivity of the remaining stock can only increase productivity to 1998 t (Fig. 6), leaving a shortfall of 102 t from the TAC. If the TAC is not reduced, then this shortfall must come from the stock biomass, depleting the legal-sized biomass below the most productive level. This would mean that the shortfall of surplus production to TAC would become larger and the fishery would proceed to collapse if further changes were not made to the management. The biomass level in the MPA reaches an equilibrium but the in biomass outside the MPA continues to decline and the fishing mortality to increase (Fig. 7). The fishery is no longer operating sustainably. Because the biomass shortfall in the example is relatively small compared with the legal biomass open to fishing, it takes decades for the depletion levels to become critical and therefore this depletion may be difficult to detect in real, wild populations (Fig. 7), especially in the stochastic environment of real populations.

In this case, introducing an MPA leads to a continually increasing level of fishing mortality outside the MPA (Fig. 7, left panel), potentially leading to a fishery collapse. The legal-size biomass outside the MPA (Fig. 7, right panel) declines steadily while the biomass inside the MPA increases and attains a new equilibrium. The time taken for the decline in legal-size biomass (25+ years) means that it might be difficult to detect such changes in wild populations (Haddon *et al.* unpublished).

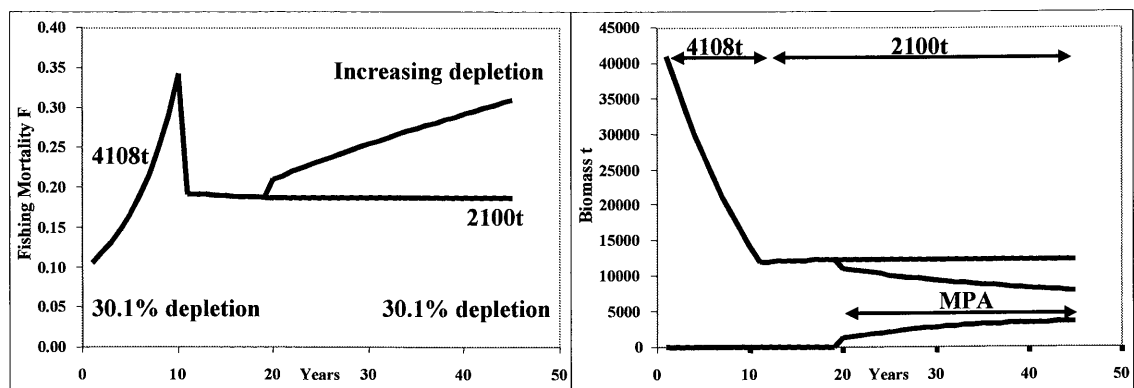


Fig. 7. Impact (modelled) of introducing a marine protected area (MPA) into a rock lobster fishery that is near to its maximum production level, relative to the scenario of no change.

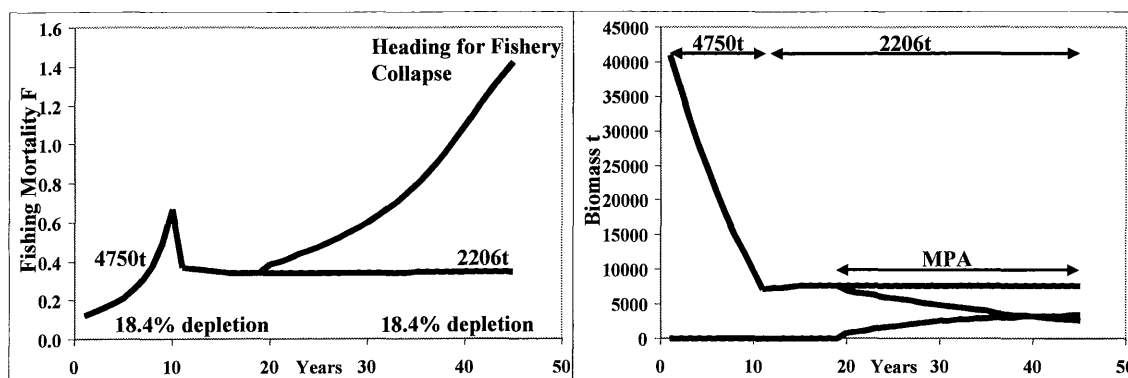


Fig. 8. Impact (modelled) of introducing a marine protected area (MPA) into a rock lobster fishery at or below its maximum production level, relative to the scenario of no change.

Introduction of an MPA when stock is already depleted

If a stock is already depleted to a level at or below the maximum productivity, the impact of introducing an MPA on the dynamics is more immediate and severe than previously seen. This occurs because none of the shortfall in catch can be made up from an increase in productivity brought about by further depleting the legal-size biomass. The legal biomass within the MPA reaches an equilibrium but the legal biomass outside the reserve declines at an increasing rate while the fishing-mortality rate increases in an accelerating fashion until the fishery collapses (Fig. 8).

In such a case, introduction of an MPA leads to a rapidly increasing level of fishing mortality outside the MPA (Fig. 8, left panel), leading to a fishery collapse. The legal-size biomass outside the MPA (Fig. 8, right panel) declines steadily while the biomass inside the MPA increases and attains a new equilibrium. The rate of change of the stock status is rapid relative to the scenarios previously considered. Consequently, it is more likely that these predicted effects could be detected in real, wild populations.

Effect of movement between population areas

A proportional movement rate of 1% of all size classes between adjacent areas was assumed in all the previous cases. This level would be a relatively generous rate of movement for Tasmanian rock lobster across the boundaries of the statistical catch-reporting area used in the model (Gardner *et al.* in press). Nevertheless, to investigate the importance of movement across reserve boundaries, different proportional rates of movement were examined for their effects (Fig. 9). Because all populations are set equal, when there

is no MPA the degree of movement has no net effect because losses are offset against gains.

In this example (Fig. 9), an MPA is introduced after the population is already in a depleted state (cf. Figs 7 and 8). With no MPA, a sustainable level of catch is achievable leading to a constant fishing mortality. With only 1% movement, a 10% MPA leads to rapidly increasing fishing mortality and fishery collapse. When there is 10% or 30% movement, which is highly unrealistic for other species and southern rock lobster but may be appropriate for some fishes, the depletion rate is greatly reduced and movement towards fishery collapse is greatly slowed, although further depletion of legal-size biomass certainly occurs.

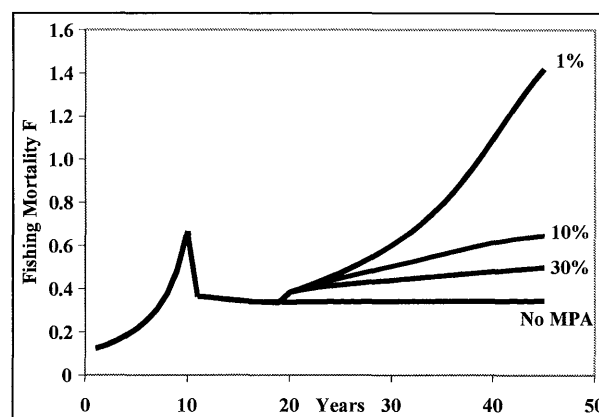


Fig. 9. Effects (modelled) of introducing a marine protected area (MPA) as modified depending on the proportional movement of rock lobsters between population areas.

A high proportion of movement can certainly ameliorate the impacts of an MPA on the remaining fishery. However, this has a negative effect on the success of the MPA (Fig. 10). A high

level of movement out of an MPA reduces the effectiveness of the closed area in terms of its ability to increase biomass and produce recruitments. As the proportion of movement increases, the size distribution of animals in the reserve moves towards the size distribution seen in the open areas when there is no MPA. However, there is little impact on the size distribution of animals found in the populations still open to fishing (Fig. 10).

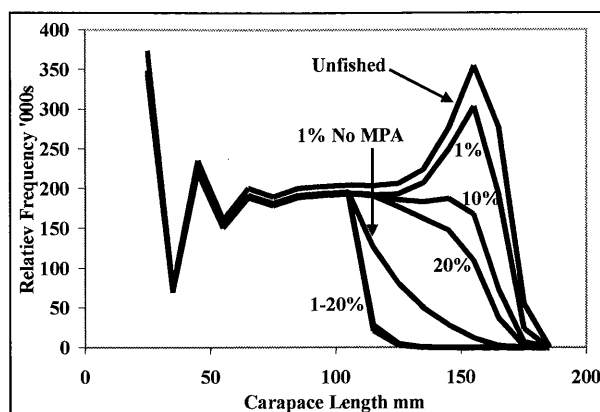


Fig. 10. Effect (modelled) of introducing a marine protected area (MPA) on the size structure of males when a rock lobster stock is already depleted with different proportional movement rates.

With no MPA, the proportion of movement does not affect the final outcome because all populations are equal and gains balance losses. In the unfished state the accumulation of older males leads to a peak of larger animals (Fig. 10). With 1% movement and no MPA, this accumulation is fished down leaving a reduced size structure in which there are still animals up to 150 mm and greater in carapace width. When an MPA is introduced the fishery collapses and the size structure of the open populations is reduced to a remnant just above the legal minimum length. The size distribution within the closed area approximates the unfished distribution. When there is 10% or 20% movement there is hardly any change to the size structure of the fished populations because any fish that leave the reserve are quickly taken in the fishery. However, the size structure in the closed area rapidly depletes away from the unfished levels and moves towards that of the state seen with 1% movement and no MPA. There is still a wider range of sizes available at greater proportions in the MPA but its effectiveness is greatly reduced.

DISCUSSION

The conclusions in this modelling study clearly relate to a specific set of conditions and biological assumptions imposed on the data. Nevertheless, the conclusions drawn are sufficiently general to be applied to other similar fisheries. Of great interest is the fact that the stock depletion that occurs in the populations that remain open may occur at such a slow rate as not to be detectable until stock depletion is far advanced towards fishery collapse. Such slow depletions towards eventual collapse would provide a challenge for any management regime. We observed that when the fishery was in a collapsed state, an MPA might provide a fishery with further catch (albeit a greatly reduced one). However, it is only when the fishery collapses and the biomass inside the reserve becomes similar to the biomass outside the reserve that any positive effects are felt. As a partial step in the recovery from a fishery collapse (along with greatly reduced catches or total closure), there may be some advantages to an MPA. Otherwise, where conventional fishery-management methods were producing positive effects, MPAs produced only negative effects on the fishery. However, if the modelling is continued until the fishery collapses, the modelling is clearly unrealistic. In countries where relevant legislation exists, it is hoped that when signs of imminent fishery collapse became apparent, catch effort is restrained to prevent such an event from occurring. The large MPAs protect against stock collapse but not fishery collapse.

The Tasmanian rock lobster fishery, for example, already has effective limits on effort and catch. There is evidence that the stock has begun to rebuild since the introduction of the quota management system. In this instance, modelling the fishery indicates that conventional fishery management will lead to a more positive fishery result than could be achieved if large MPAs were introduced.

In summary, because the effects of large MPAs (> 5% coast) tend to become apparent only over many years, the effects of small MPAs (< 0.5% coast) would be hard to detect. Again, because of the dynamics of growth and recruitment, there is a time lag before any positive effects of an MPA become apparent. In an exploited population, introduction of an MPA is equivalent to an increase in the TAC outside the reserve. Introduction of an MPA without a reduction in catch may have a negative effect upon some fisheries. The impact of introducing an MPA will depend on the biology of the species concerned, the state of depletion of the stock, and whether the catch is to be reduced appropriately. If the stock is already in a depleted state, an MPA can hasten fishery collapse.

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